L Number	Hits	Search Text	DB	Time stamp
1	55567	refractive adj5 index	USPAT	2003/03/26 10:42
2	82672	(silicon adj nitride) or "SiN"	USPAT	2003/03/26 10:43
3	800	(refractive adj5 index) with ((silicon adj nitride) or "SiN")	USPAT	2003/03/26 10:43
4	570	(refractive adj5 index) near5 ((silicon adj nitride) or "SiN")	USPAT	2003/03/26 10:44
5	56129	silicon adj dioxide	USPAT	2003/03/26 10:45
6	439	(refractive adj5 index) near5 (silicon adj dioxide)	USPAT	2003/03/26 11:01
7	21	"Si.sub.3N.sub.4"	USPAT	2003/03/26 11:02
8	17939	"Si.sub.3 N.sub.4"	USPAT	2003/03/26 11:02
9	158	(refractive adj5 index) near5 "Si.sub.3 N.sub.4"	USPAT	2003/03/26 11:33
10	46247	multilayer	USPAT	2003/03/26 11:33
11	148134	dielectric	USPAT	2003/03/26 11:34
12	6534	multilayer same dielectric	USPAT	2003/03/26 11:34
13	778554	thickness	USPAT	2003/03/26 11:34
14	15618	(refractive adj5 index) same thickness	USPAT	2003/03/26 11:34
15	196	(multilayer same dielectric) same ((refractive adj5 index) same thickness)	USPAT	2003/03/26 11:50
16	188510	spectrum	USPAT	2003/03/26 11:50
17	15	((multilayer same dielectric) same ((refractive adj5 index) same thickness)) same spectrum	USPAT	2003/03/26 11:53
18	13485	((silicon adj nitride) or "SiN") same (silicon adj dioxide)	USPAT	2003/03/26 11:54
19	2267	"Si.sub.3 N.sub.4" same (silicon adj dioxide)	USPAT	2003/03/26 11:54
20	5051	thickness same (((silicon adj nitride) or "SiN") same (silicon adj dioxide))	USPAT	2003/03/26 11:54
21	5051	thickness same (thickness same (((silicon adj nitride) or "SiN") same (silicon adj dioxide)))	USPAT	2003/03/26 11:54
22	870	thickness same ("Si.sub.3 N.sub.4" same (silicon adj dioxide))	USPAT	2003/03/26 11:55
23	0	"70.nm."	USPAT	2003/03/26 11:55
24	0	".nm."	USPAT	2003/03/26 11:55
25	188097	nm	USPAT	2003/03/26 11:55
26	3172	"70 nm"	USPAT	2003/03/26 11:56
27	1	(thickness same ("Si.sub.3 N.sub.4" same (silicon adj dioxide))) same "70 nm"	USPAT	2003/03/26 11:56
28	14	(thickness same (thickness same (((silicon adj nitride) or "SiN") same (silicon adj dioxide)))) same "70 nm"	USPAT	2003/03/26 11:56
29	14	((thickness same ("Si.sub.3 N.sub.4" same (silicon adj dioxide))) same "70 nm") or ((thickness same (thickness same (((silicon adj nitride) or "SiN") same (silicon adj dioxide)))) same "70 nm")	USPAT	2003/03/26 12:30
30	688	blue adj4 shift	USPAT	2003/03/26 12:31
32	0	("Si.sub.3 N.sub.4" same (silicon adj dioxide)) and (blue adj4 shift)	USPAT	2003/03/26 12:31

31	3	(((silicon adj nitride) or "SiN") same (silicon adj dioxide)) and (blue adj4 shift)	USPAT	2003/03/26 12:33
33	5558	((refractive adj5 index) same thickness) same wavelength	USPAT	2003/03/26 12:33
34	136	(multilayer same dielectric) same (((refractive adj5 index) same thickness) same wavelength)	USPAT	2003/03/26 12:34
35	533945	absor$5	USPAT	2003/03/26 12:34
36	106	((multilayer same dielectric) same (((refractive adj5 index) same thickness) same wavelength)) and absor$5	USPAT	2003/03/26 13:22
37	9057	quarter adj4 wave	USPAT	2003/03/26 13:23
39	0	("Si.sub.3 N.sub.4" same (silicon adj dioxide)) same (quarter adj4 wave)	USPAT	2003/03/26 13:23
38	8	(((silicon adj nitride) or "SiN") same (silicon adj dioxide)) same (quarter adj4 wave)	USPAT	2003/03/26 14:07
40	54683	silicon adj3 substrate	USPAT	2003/03/26 14:08
41	135253	silver	USPAT	2003/03/26 14:08
43	59789	reflector	USPAT	2003/03/26 14:10
44	6	((silicon adj3 substrate) with silver) same reflector	USPAT	2003/03/26 14:11
45	15	((silicon adj3 substrate) with silver) same mirror	USPAT	2003/03/26 14:11
42	190	(silicon adj3 substrate) with silver	USPAT	2003/03/26 14:17

MODULE 6-5

MIRRORS AND ETALONS

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(1) A mirror is a smooth surface that can reflect enough light to serve a useful purpose. Mirrors have been used since man first saw his image in a calm pool of water. They have progressed from the great silver-blackened hall mirrors of the eighteenth century to where, today, they are used to reflect light within a laser cavity.

(2) This module will instruct you about the recognition and specifications of various mirror types, their limitations and their applications.

(3) Before you begin this module, you should have studied optical cavities and modes of oscillation, light rays, reflection of light, reflection of light at a plane boundary, and reflection of light at a spherical surface.

OBJECTIVES

(4) When you complete this module, you should be able to do the following:

1. Write a statement in your own words comparing the advantages and disadvantages of front- and rear-surface mirrors.
2. Explain and give one application for each of the following:

   a. Dielectric-coated metal mirror
   b. Hot mirror
   c. Cold mirror
   d. Fabry-Perot etalon
   e. Autoreflection mirror

3. Using three manufacturers' catalogs, outline a comparison of the quality and price of mirrors that meet given specifications.
4. Construct a retroreflector that gives performance satisfactory to your instructor.
5. With the aid of an appropriate diagram, explain how "ghost images" are formed and how they can be eliminated.

DISCUSSION

(5) When light strikes the surface of any object, some of the light is reflected, some is absorbed by the object, and some is transmitted through the object. The extent to which each of these processes occurs varies. Some objects transmit the major portion of the incident light, some objects absorb most of the incident light, and other objects reflect most of the incident light. Objects designed to reflect most of the light are called "mirrors."

(6) The amount of light reflected by a mirror depends on:

1. The nature of the reflecting surface (composition,

structure, density, color, and so on).

2. The texture of the reflecting surface (smooth or rough, regular or irregular, dull or polished, etc).

3. The wavelength and polarization of the light.

4. The angle at which the light strikes the surface.

(7) We will discuss some of these factors in more detail in this module.

(8) The reflection from the surface of a high-quality mirror is called "specular." This means that the rays striking the surface are reflected from the surface according to the law of reflection, $\theta_i = \theta_r$. Figure 1 shows specular reflection from a polished mirror surface.

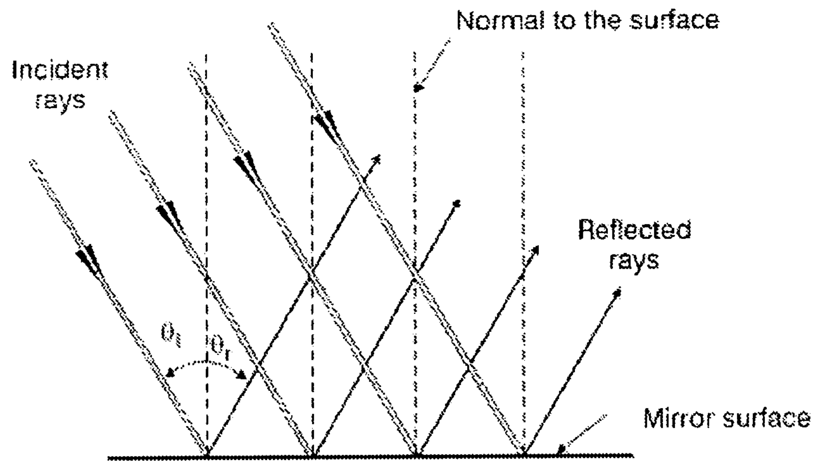


Fig. 1
Specular reflection

(9) Not all reflectors, however, are specular reflectors. Some are diffuse reflectors, which means that the rays are reflected in random directions. Figure 2 shows diffuse reflection. Common examples of diffuse reflection include the reflections from this paper and from projection screens.

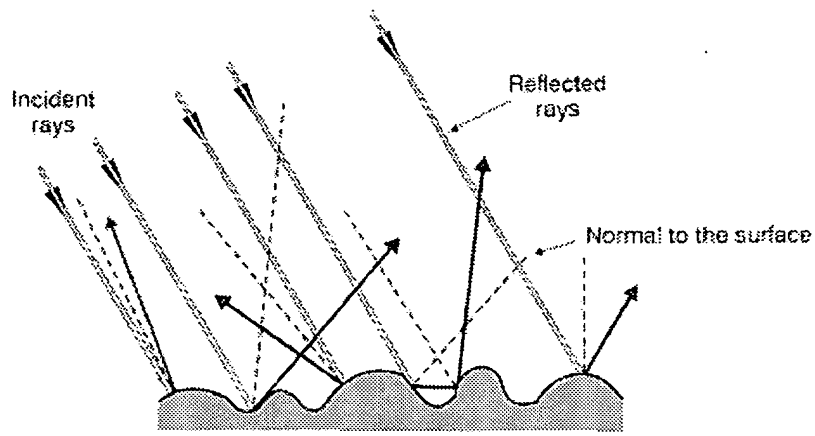


Fig. 2
Diffuse reflection

(10) Figure 3 illustrates a plane mirror used to form a virtual image by reflection. The virtual image formed by a plane mirror corresponds in size and shape to the object and is the same distance behind the mirror as the object is in front of the mirror. The image is correctly oriented from top to bottom, but the right and left parts are interchanged.

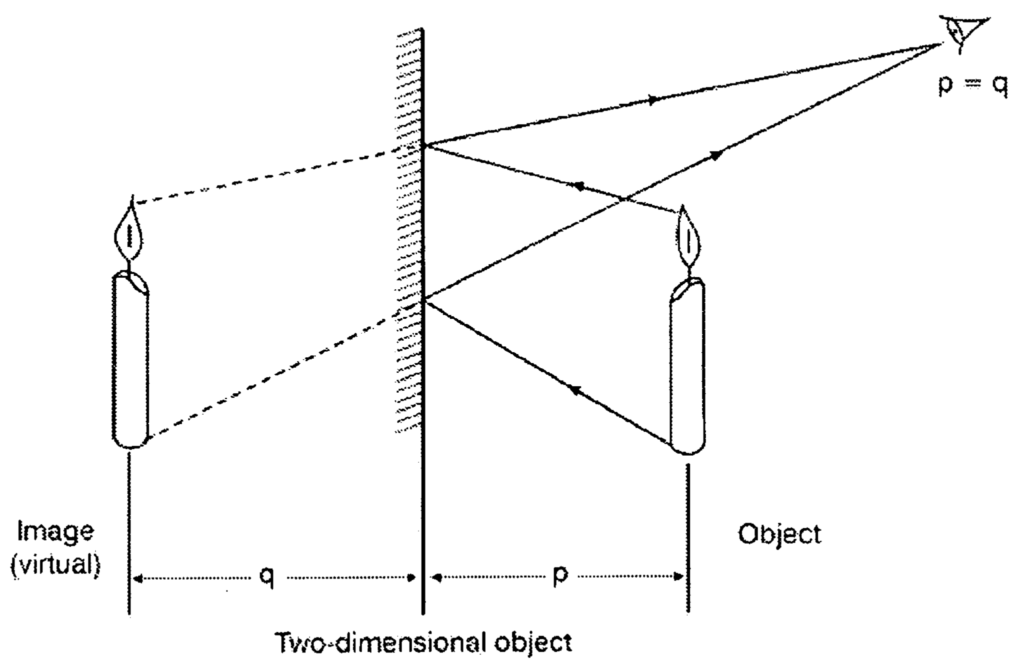


Fig. 3
Image formed by reflection

(11) To illustrate this point further, let's consider Figure 4. If the word READ is considered to be right-handed and is readable, then the mirror image of the word must be considered to be left-handed. It has been turned left for right. No matter how the word is turned, it will remain left-handed. To read it correctly, you must either use a second mirror to turn it

or turn the paper over and look at it from the other side. The image from a single surface reflection is always left-to-right inverted

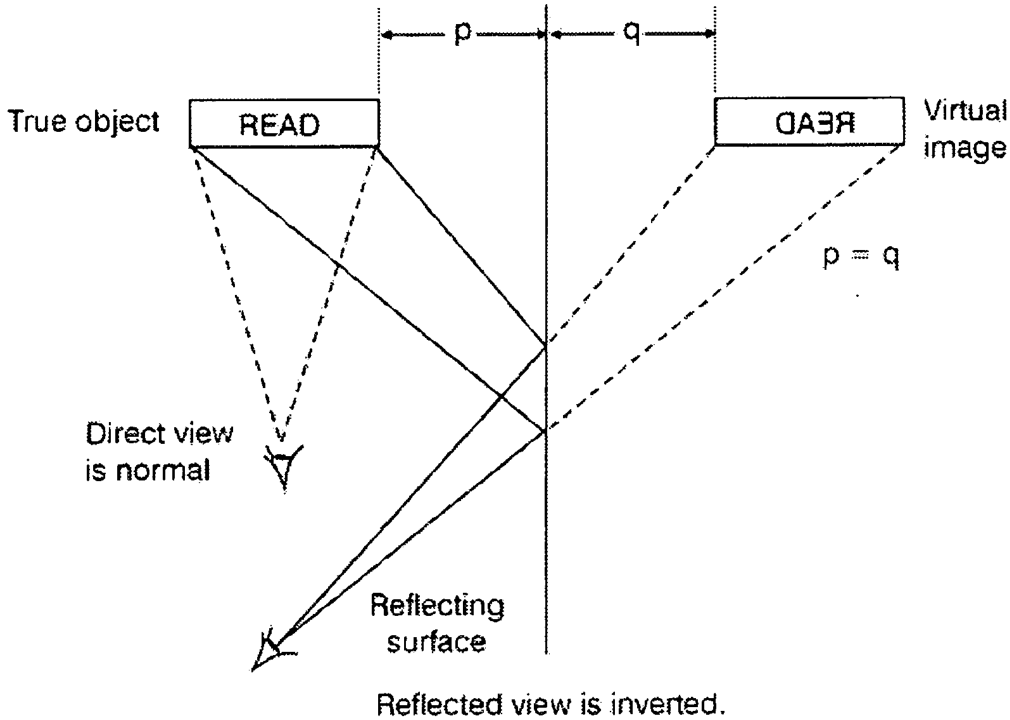


Fig. 4
Inversion of the image formed by a single surface reflection

(12) As you learned from an earlier module, curved mirrors form either real or virtual images by converging or diverging light. Inexpensive, curved, spherically convex mirrors which diverge incident rays can be used to enlarge a field of view. Such an application is the small "spot" mirror attached to the rear view mirror of an automobile. Low-quality spherically concave mirrors which converge incident light rays often are used as shaving mirrors to enlarge an image.

(13) The quality, size and reflectivity of mirrors largely determine their use. For instance, the searchlight shown in Figure 5 does not require a high-quality mirror since a focused image is not being formed by the system.

(14) The reflecting telescopes shown in Figure 6 require mirrors of very high optical quality to produce usable images. The reflectivity of the telescope mirrors doesn't have to be extremely high since a reasonable amount of light absorption in the system can be tolerated.

(15) Mirrors used for the end reflectors in laser cavities must be of high optical quality and have high reflectivity. Even small absorption or scattering losses in this application may render the system inoperable.

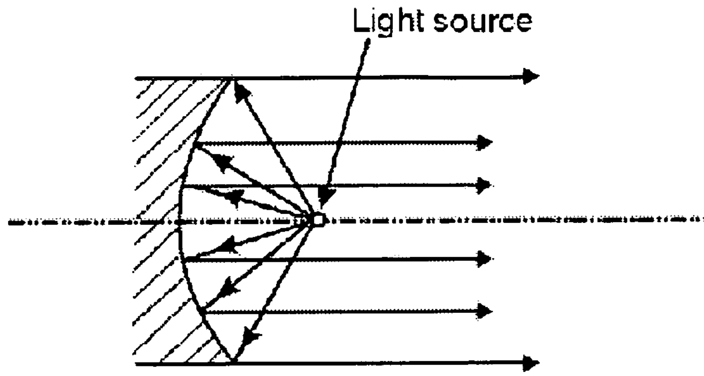


Fig. 5
Searchlight as an application of concave mirrors

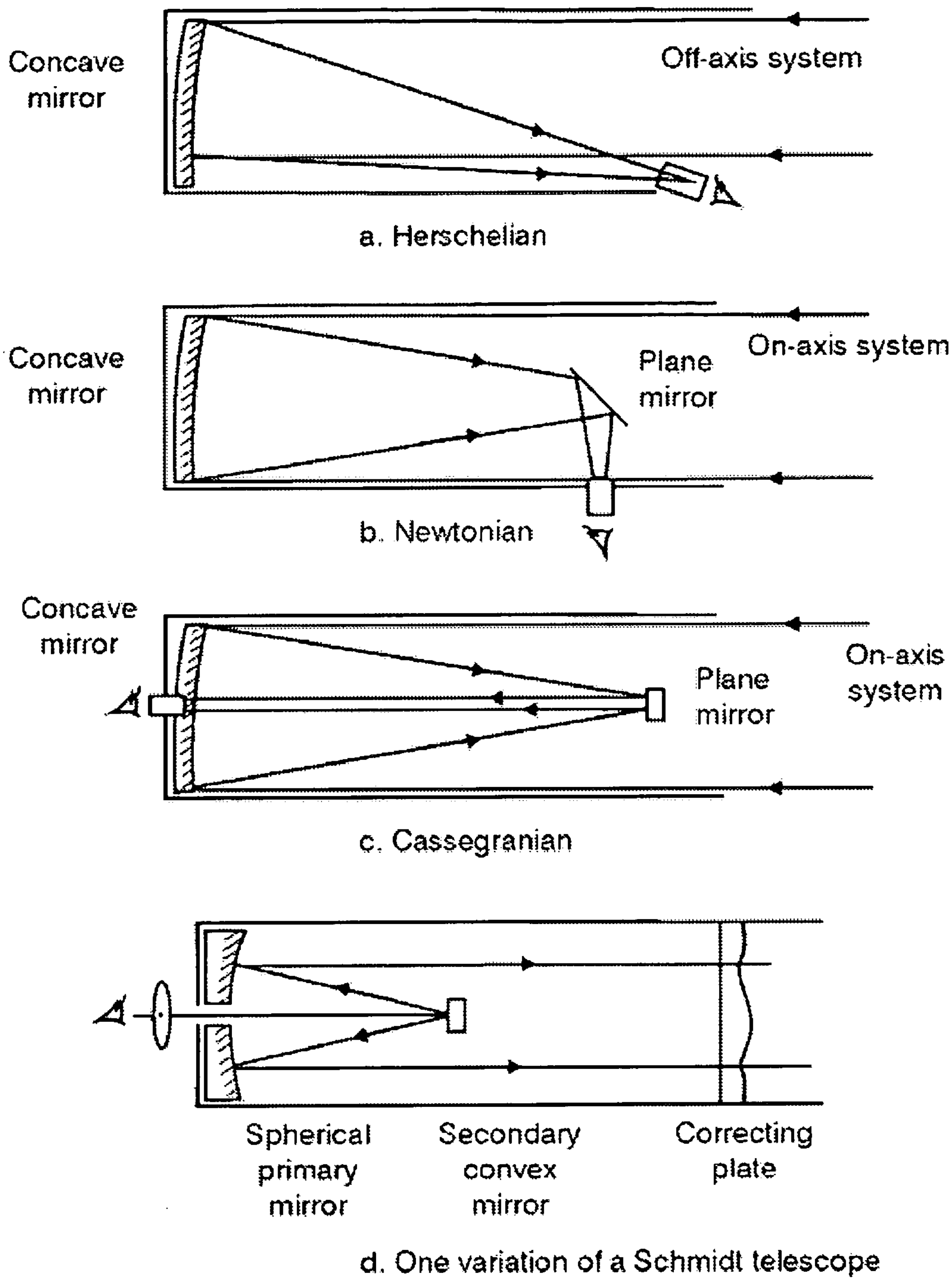


Fig. 6
Types of reflecting telescopes

Mirror Limitations

(16) Mirrors used as imaging systems suffer from many of the same defects as lenses. These defects include spherical aberration, coma, astigmatism, curvature of field, and distortion. You can find a more

complete description of these defects in a lesson on lenses.

(17) Rays of light striking the outer portions of a spherical reflecting surface don't focus at the same point as rays striking the center portion of the surface. This is known as spherical aberration. It will cause an out-of-focus image. Short-focal-length mirrors are plagued by spherical aberration more than are longer-focal-length mirrors. This is because the short-focal-length mirror has a much sharper curvature.

(18) Spherical aberration can be controlled or eliminated in several ways. If the aperture of the mirror is limited, the outside rays of light will not strike the reflecting surface. This prevents them from causing the out-of-focus image. This is normally the least expensive way to reduce spherical aberration.

(19) A more costly method is also the more perfect method. It consists of using a parabolic shape for the reflecting surface instead of the spherical shape. To understand the reason for using a parabolic shaped reflecting surface, refer to a good analytic geometry textbook.

(20) Note that, when it's used off-axis a spherical mirror may produce a better image than a comparable parabolic mirror. Parabolic mirrors usually are used in optical systems, such as telescopes, where the incident rays are nearly parallel to the mirror's axis of symmetry.

(21) A third way to minimize spherical aberration is a technique developed by Bernhardt Schmidt, the so-called "Schmidt telescope" or "Schmidt camera." In this optical system, a thin transparent "correcting plate" is placed at the center of curvature of the spherical mirror. (See Figure 6d.) The plate is essentially a specially shaped lens that corrects the spherical aberration, astigmatism and coma of the telescope's primary mirror. Schmidt telescopes are popular for applications such as small astronomical instruments where it's sometimes more cost-effective to fabricate a spherical mirror plus a correcting plate rather than a parabolic primary mirror.

(22) Astigmatism is a tendency for a mirror to focus light entering the surface vertical, with respect to a particular axis, at a different point from light entering horizontal with respect to the same axis. This defect causes images of a point to be extended into a line. All optical elements display some degree of astigmatism although it can be greatly reduced by appropriate combinations of lens and/or mirror elements.

(23) Because the quality of a mirror depends on the rigidity of the substrate material, it's usually made of some stiff material like glass. In

less stringent applications plastic may suffice and in more severe applications, materials more rigid than glass may be necessary. The substrate material must be thick enough to minimize distortion of the mirror surface. It is also advisable to mount the mirror on three support points only, to avoid stress-induced distortion.

(24) When glass is used as the mirror substrate, reflection from an uncoated front surface generally will produce a "ghost image." The "ghost image" is slightly displaced from the main image that arises from the highly reflective rear surface. For this reason most high-quality mirrors are made with front or first reflecting surfaces on top of the glass substrate.

(25) Many optical systems can operate very well even with low-quality mirrors. Other systems require one or all the defects to be minimized. A mirror of too low quality may hinder the operation of your equipment or decrease its accuracy. Too good a mirror may represent a needless expense. As discussed later, mirror quality must be related to its application.

Reflecting Surfaces

(26) To obtain high specular reflectance, the polished glass or plastic surface can be coated with a metallic layer. Silver was the classical material used for this purpose. A highly polished silver surface reflects ~ 95% of the incident light in the visible range. Silver, however, has to be protected from tarnishing. So it has been largely replaced by aluminum evaporated onto the polished substrate in a high vacuum. On contact with the atmosphere, a thin layer of aluminum oxide forms on the surface of the aluminum film and provides some protection. Other protective coatings or "overcoats" often are needed. These will be mentioned later.

(27) The reflectance of metals depends on the wavelength, the surface preparation, the angle of incidence, and specific properties of the metal itself. Figure 7 shows the variation of the reflectance of a number of typical metals as a function of visible wavelength.

(28) Silver and aluminum are of particular importance for general use because they maintain their high reflectance throughout the visible spectrum. It's now standard practice to coat the mirrors of large telescopes, such as the 200-inch Hale reflecting instrument at Mt. Palomar, with evaporated aluminum. For reflecting surfaces where the small advantage of silver over aluminum is important, as in Fabry-Perot

etalons, silver is preferred. For use with visible and infrared light, silver is also preferred. But for ultraviolet light aluminum is better, and gold may be preferred at longer wavelengths.

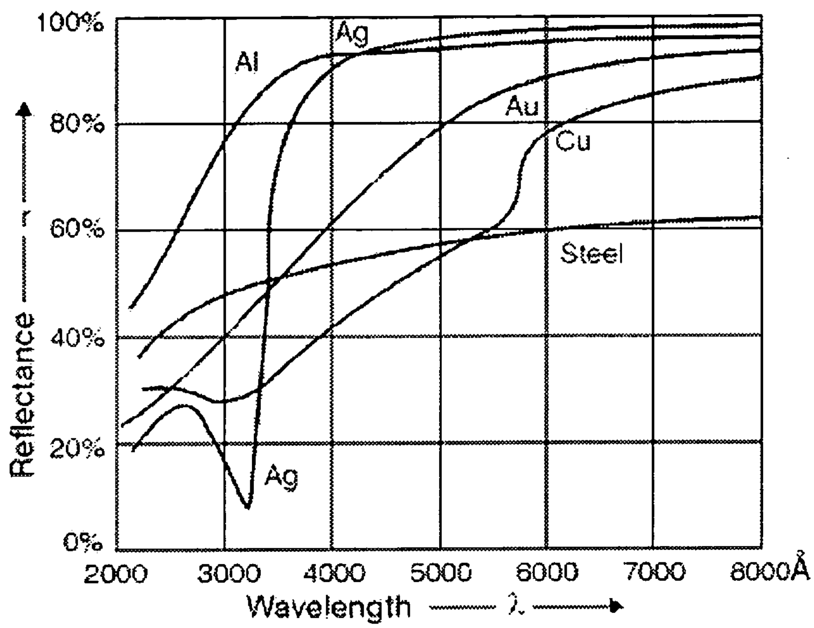


Fig. 7
Reflectances at normal incidence of aluminum, silver, gold, copper, and steel

(29) As was mentioned earlier, some metals (aluminum) form their own protective layer. This layer is very thin, however, and it is usually advisable to provide additional protective coatings. Silicon monoxide frequently is used for this purpose. It causes some reduction in reflectance, but this reduction is less than is experienced by aging processes. Magnesium fluoride also can be used as a protective coating. The effect of these two coatings on the reflectance of aluminum is shown in Figure 8.

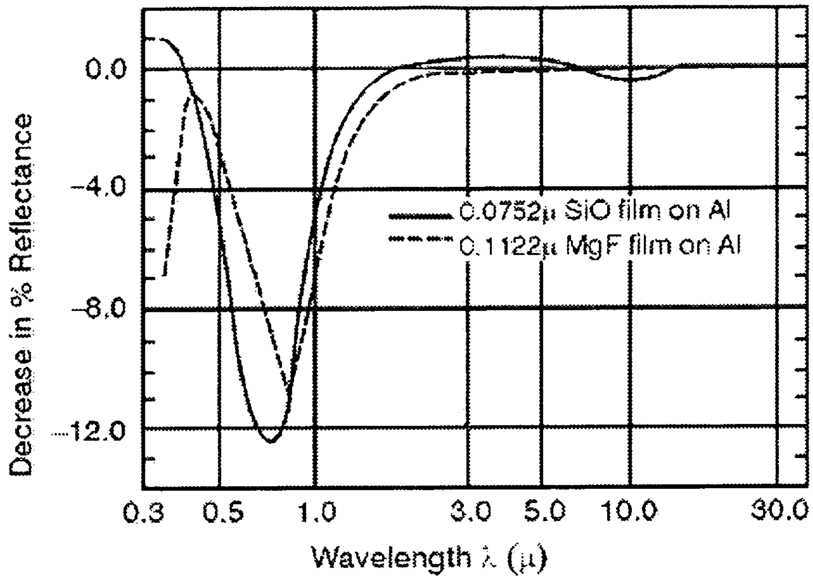


Fig. 8
Spectral reflectance of coated aluminum mirrors

(30) You should note from Figure 8 that different protective coatings affect the reflectivity differently as a function of wavelength. For example, if you needed a mirror for reflecting light of 2-micrometers wavelength, silicon monoxide would be best. If 10 micrometers were the area of interest, magnesium fluoride would be the better choice.

(31) In some applications that involve multiple reflections—such as a laser cavity—even the high reflectance of the metals shown in Figure 7 may not be enough. Surfaces that have a higher reflectance than any metal can be produced. These surfaces generally are composed of several dielectric materials and use the principle of interference to produce high reflectance values.

(32) The dielectric or multilayer film mirrors sometimes are combined with a metal mirror to improve the reflectance. Figure 9 shows the reflection enhancement of a metal mirror due to multilayer coatings. The dielectric materials in Figure 9 are zinc sulfide and cryolite, both vacuum deposited on a metal mirror to a highly controlled thickness.

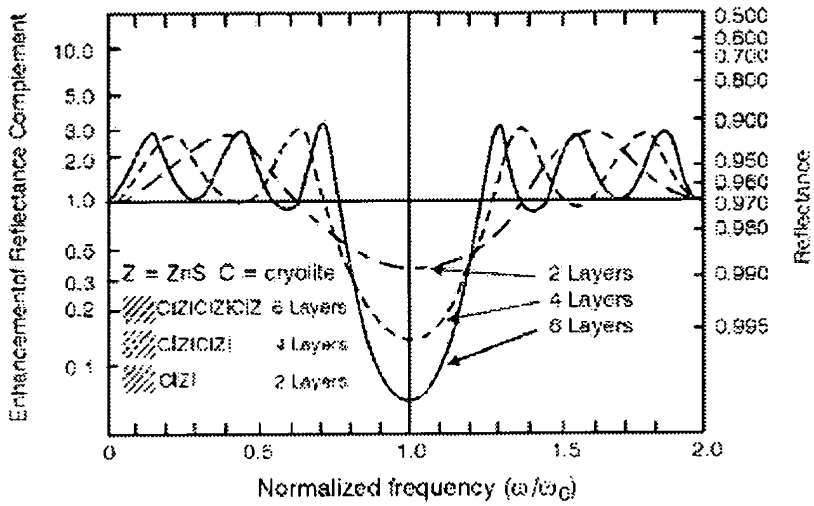


Fig. 9
Enhancement of spectral reflectance at a specific wavelength due to multilayer coatings

(33) Notice that reflectances very near to 100% can be achieved by this method. The high reflectance does not, however, extend over as great a wavelength range as does that of bare metals. The reflectance of a dielectric or dielectric coated metal is peaked very strongly around a particular wavelength of light. The reason for this should become apparent in the following discussion.

(34) Consider Figure 10. The incident light is divided into two different beams by a partially reflecting surface. Each of these beams travels a different distance and interference is observed when these two rays recombine. As shown in Figure 10 the light from the source impinges upon surface S_1. Part of this beam is reflected at a point A. The remainder penetrates the medium between the two surfaces S_1 and S_2 and reflects back and forth between them. The thickness of the dielectric is h_1, and θ_1 is the angle of incidence in the medium of index of refraction n_1.

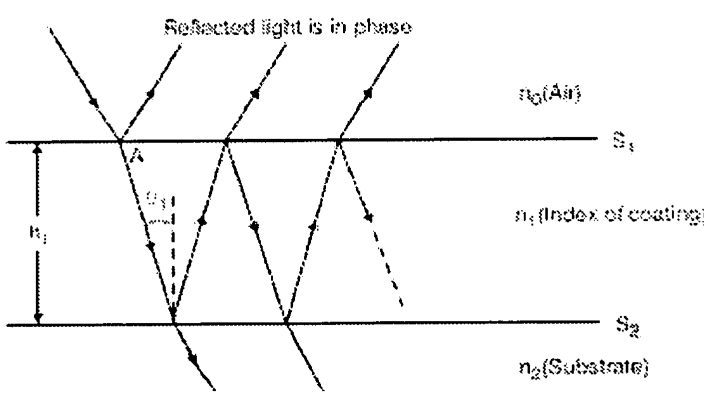


Fig. 10
Reflection from a single thin-film coating layer

(35) If the reflectance of the surfaces is low, the beam may reflect only once before it's greatly attenuated. If the reflectance is close to unity, it may reflect as many as 30 times. In either case, the beams that reflect from either side of the film have traveled different optical paths and interference is observed when they recombine.

(36) If several dielectric films—each a quarter wave thick and with alternately high and low index of refraction—are stacked, the reflected beams from all the interfaces are in phase upon leaving the uppermost boundary. This situation is shown in Figure 11.

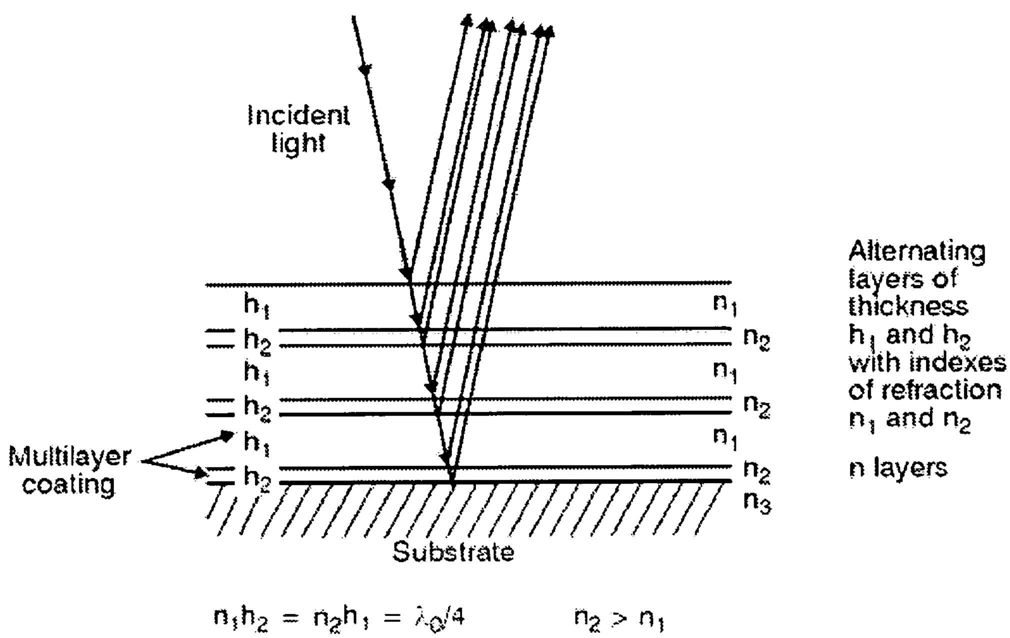


Fig. 11
Operation of a multilayer dielectric coating

(37) Note that light may reflect many times before returning to the upper surface. But when it does this, it's in phase and going the same direction as all the other reflected light rays. Modern coating technology produces reflectances in excess of 99.999% using approximately 20 layers in a dielectric "stack."

(38) You can see in Figure 12 that the reflectance of a dielectric mirror is a strong function of the wavelength of the incident light. The angle of incidence, as well as the specific properties and construction of the dielectric coating are also important mirror parameters. If either of these parameters changes, the light may not travel the right distance through the coating to be in phase at the upper boundary.

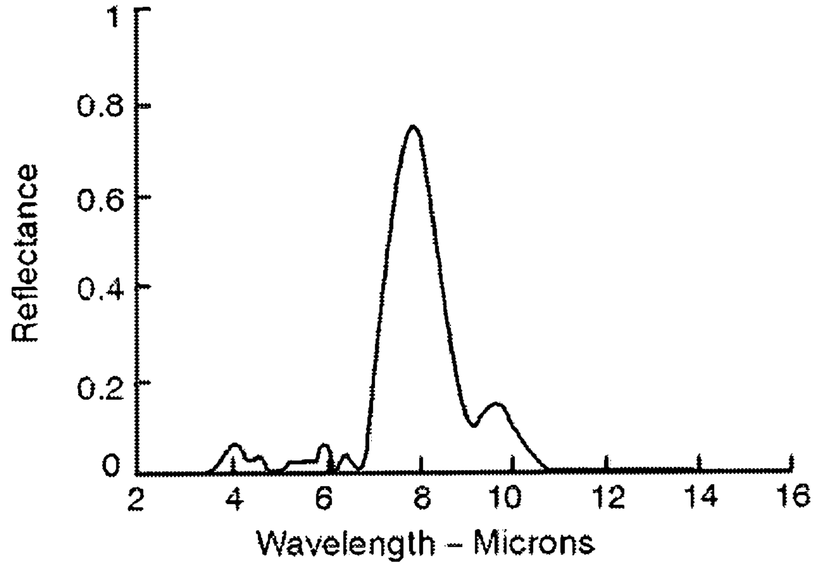


Fig. 12
Experimental curve of reflectance of a three-layer dielectric mirror as a function of wavelength

(39) Figure 12 shows the reflectance of a three-layer dielectric mirror as a function of wavelength. The curve would be even narrower and the peak higher if more dielectric layers were used.

(40) Multilayer dielectric mirrors have been devised for use in the ultraviolet (220 nm) to the infrared (20 μm). A difficulty met in the ultraviolet is that most high-index materials, such as zinc sulfide and titanium dioxide, are absorbing. So you must use materials with a lower refractive index. Antimony trioxide and lead fluoride are good examples of low-refractive-index materials.

(41) Laser end reflectors are very common examples of multilayer dielectric mirrors. When you specify such reflectors you must consider a number of items. The mirror must be chosen for use at the desired wavelength. Diameter and thickness must be chosen to coordinate with the size of the mirror mounts to be used. The curvature of both surfaces of the mirror must be specified to match the type of laser cavity and the cavity length. The reflectivity, scattering and absorption at the particular wavelength being used must be a major consideration.

(42) Substrate material and surface quality also must be specified. Manufacturers specify surface quality as being flat to a fraction of a wavelength. This flatness is determined by observing the interference pattern produced when the surface is compared to a "perfect" master flat.

(43) The flatness of a mirror (or other optical components such as a

window's) surface should be matched to the intended application. For example, wave-front distortion can usually be tolerated in laser material-processing applications such as heat treating and welding. The beam-steering optics in such systems can be of relatively poor flatness—1/4 λ should suffice.

(44) On the other hand, in many laser applications wave-front distortion must be minimized. As an example, the optics in holographic systems should be of high surface quality to preserve the phase information. Surface flatness of 1/20 λ is often desirable. Similarly, the plane cavity mirror and Brewster windows used in many lasers usually are specified to at least 1/10 λ flatness to ensure good output beam quality.

(45) Note that, unless otherwise specified, optical flatness is measured with respect to the two yellow Sodium D lines (5890 Å and 5896 Å) that historically have been used as a convenient standard (almost) monochromatic light source for optical measurements.

(46) A more complete discussion of flatness specifications is given in Module 6-4, "Windows and Flats."

(47) Durability of the surface coating usually is specified rather vaguely. But you should consider it when a laser and reflector are to be chosen.

(48) One application of multilayer mirrors of particular importance is heat control in projection systems. In most projection systems, a mirror is placed behind the projection lamp to direct the maximum amount of light toward the film. Formerly these mirrors were coated with silver, but this reflected the infrared heat as well as the visible light toward the film. This problem is solved if you use a "cold" mirror instead of the silver. The cold mirror is a multilayer coating that has a high reflectance in the visible spectral region and a high transmission in the near infrared. As shown in Figure 13, this allows the infrared to pass through the rear of the lamp housing.

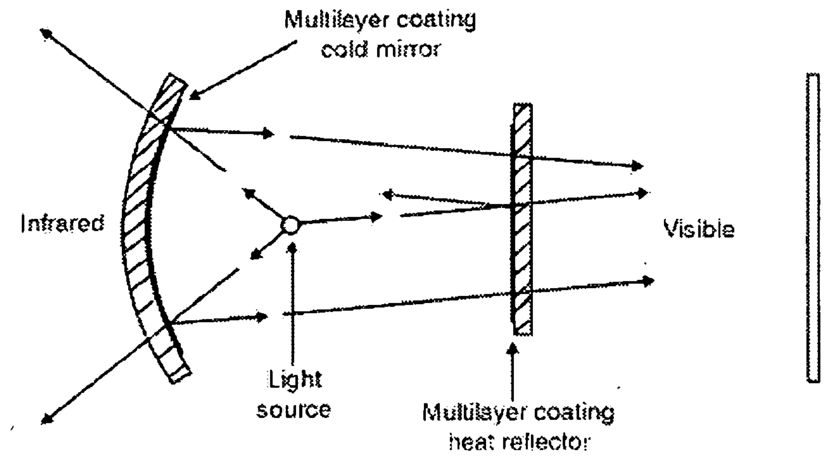


Fig. 13
Use of cold mirror and heat reflector in a projection light source

(49) The performance of such a system is increased even more if a heat reflector is inserted between the lamp and the film. The heat reflector is a mirror in the infrared and a high transmission window in the visible. This reflects even more of the heat from the film. In practice this combination of mirrors can result in a two-to-three times reduction in heat incident on the film. A similar arrangement could be used to pump a laser cavity at the desired wavelength and keep heat-loading to a minimum.

Fabry-Perot Etalon

(49a) A Fabry-Perot etalon inserted in a laser cavity makes use of mirrored surfaces arranged in a particular geometry to achieve a narrowing of the wavelength spread of the emitted laser light. A Fabry-Perot *etalon* is nothing more than a Fabry-Perot *interferometer* with a *fixed distance* between the two mirrors found in the interferometer. To understand the operation of an etalon, we need first to see just how a Fabry-Perot interferometer works to favor one wavelength over another.

Fabry-Perot Interferometer

(49b) A typical arrangement for a Fabry-Perot (FP) interferometer is shown schematically in Figure 14. Two thick glass plates are used to enclose a plane parallel section of air of thickness t between

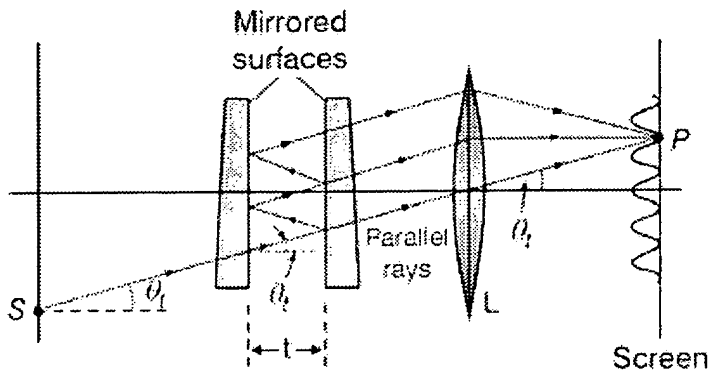


Fig. 14
Fabry-Perot Interferometer.

them. The important surfaces on the glass plates are the inner ones, between which light is multiply reflected, as shown. The mirror surfaces are generally polished to a flatness of $\lambda/50$ and coated with a highly reflective layer of silver or aluminum. Silver films—around 50 nm thick—are generally used when visible light passes through the FP interferometer; aluminum is used for UV light (below 400 nm) since reflectivity of silver drops off sharply below 400 nm. The outer surfaces of each glass plate are "tilted" at a slight angle relative to the inner surfaces (several minutes of arc) as shown. This is done to eliminate spurious interference patterns that would otherwise arise from reflected beams occurring between the parallel surfaces of the glass plates themselves.

(49c) As drawn in Figure 14, if a ray of monochromatic (single wavelength) light from point S passes through the first glass plate, it then undergoes multiple reflections between the two inner mirror surfaces. Since the reflectivity of the two mirrors is not 100%, some of the reflected light at the second surface passes through the second plate and is focused by converging lens L on the screen at point P. If the spacing t between the plates satisfies the condition $t \cos \theta = m(\lambda/2)$ for an incident angle θ_t, the spot at P is bright. If not, it is dark. As θ_t changes the condition for interference changes, giving rise to the bright and dark fringes show on the screen.

(49d) If an extended source—rather than a point source—is used, and the plate spacing t is kept fixed, the arrangement shown in Figure 15 gives rise to a pattern of concentric fringes—as shown. In this arrangement, collimating lenses L_1 and L_2, located before and after the two plates, are used to produce the fringe pattern on the screen.

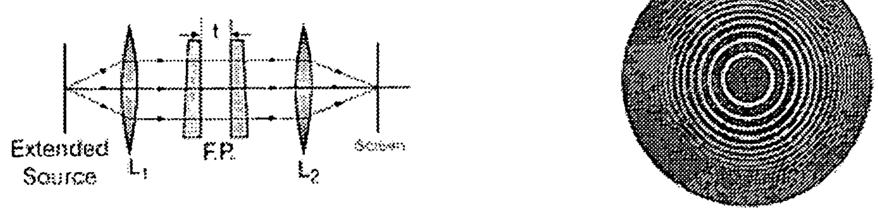


Fig. 15
Fabry-Perot interferometer—used with an extended source, fixed spacing t and collimating lenses L_1 and L_2—gives rise to a pattern of concentric circular rings.

(49e) Figure 16 shows a *Fabry-Perot etalon* (mirror spacing t is fixed) in tandem with a prism spectrometer. In this arrangement the prism spectrometer separates the concentric ring patterns formed for the different wavelengths of light, producing patterns for red, green, and violet light, for example, as shown:

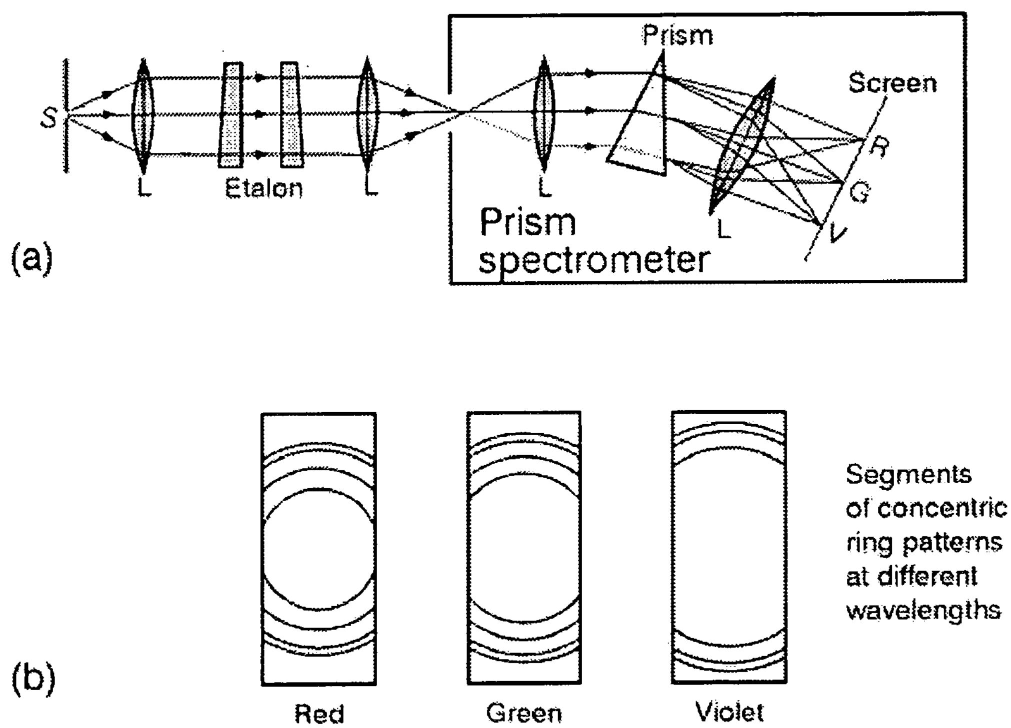


Fig. 16
Fabry-Perot etalon and prism spectrometer (a) working together to produce (b) different concentric ring patterns (partial representation shown) at different wavelengths.

Effect of Fabry-Perot Etalon in a Laser Cavity

(49f) Based on the brief discussion of the Fabry-Perot interferometer presented above, we can draw the following important conclusions:

- If light of a given wavelength λ is incident normally on a pair of mirrors in the FP interferometer, **and** if the spacing between the two mirrors is such that a whole number of half wavelengths fits within the mirror spacing t—that is, if ($m\ \lambda/2 = t$), where m is an interger—then the FP interferometer passes most of the incident light. Under this condition, one often says that the FP interferometer is *resonant* to the particular wavelength λ. This condition is shown schematically in Figure 17a.

- If light of a given wavelength λ is incident normally on a pair of FP mirrors and the resonance condition ($m\ \lambda/2 = t$) is **not** satisfied, then most of the incident light is rejected (reflected). In this case, the FP interferometer is said to be *nonresonant* to the incident light. This condition is shown schematically in Figure 17b.

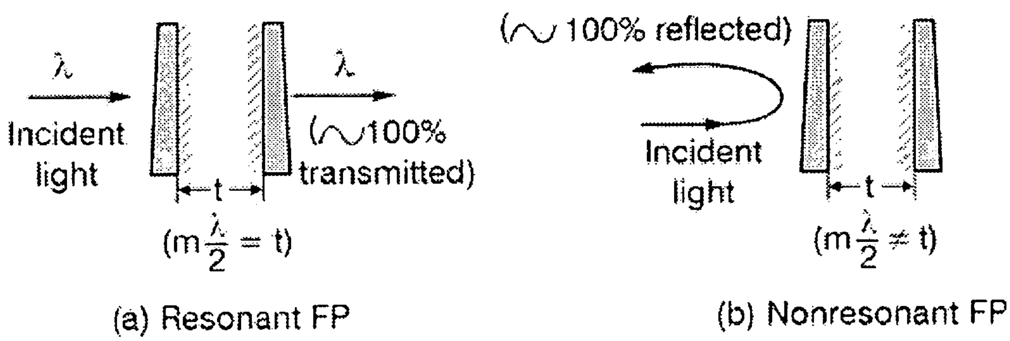


Fig. 17
Resonant and nonresonant Fabry-Perot arrangements.

(49g) Now let us ask what happens when a FP etalon—of fixed spacing—is placed in a laser cavity. Figure 18 shows such an arrangement, with an *aperture*, *gain medium* and *FP etalon* inserted between the laser mirrors. The aperture, when sufficiently "stopped down," prevents all higher order transverse modes from oscillating in the cavity, permitting, say, only the TEM_{00} mode to survive.

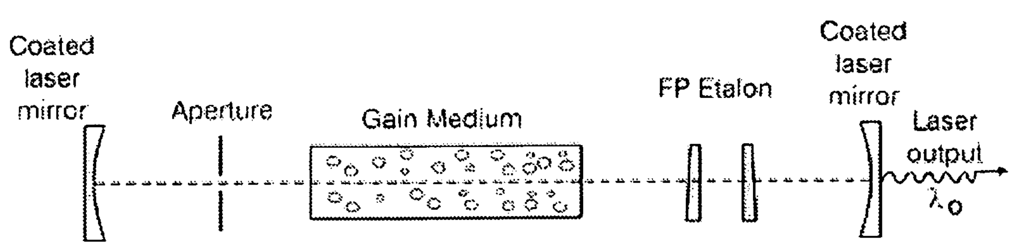
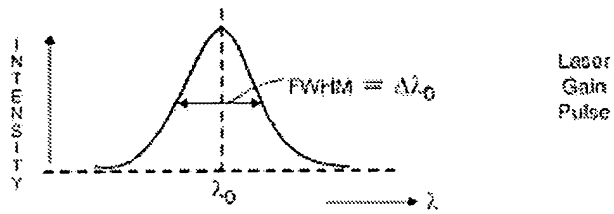


Fig. 18

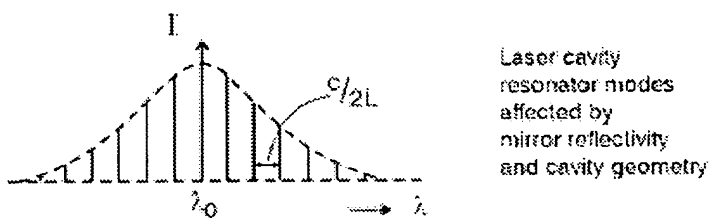
Laser cavity with aperture and FP etalon to produce a single transverse and single longitudinal oscillating mode, thereby emitting a very narrow laser output.

(49h) Based on the physics of laser action we learned about in Course 2 on *Introduction to Lasers*, let's review the action of the elements in Figure 18 which contribute to a narrowing of the laser pulse.

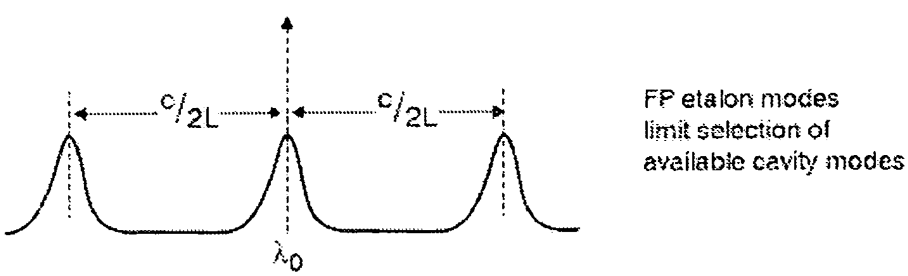
- As a result of population inversion and stimulated emission in the *laser gain medium*, a laser pulse—with a FWHM of $\Delta\lambda_o$ around λ_o is formed, as sketched below:



- Laser cavity mirrors, appropriately coated to reflect the laser light back and forth efficiently, and spaced a distance L apart, give rise to longitudinal modes in the cavity separated by a distance c/2L, where c is the speed of light in vacuum. The combined effect of the laser pulse, mirror reflectivity and cavity resonance produces the longitudinal cavity modes shown below:

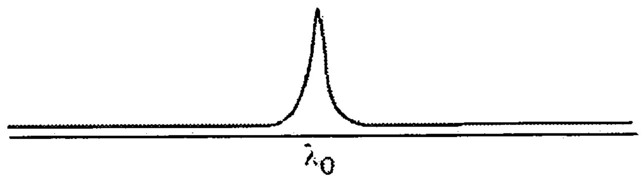


- The Fabry-Perot etalon resonant to wavelengths which satisfy the condition m $\lambda/2$ = t—where t is the spacing of the FP mirrors—transmits its own series of longitudinal modes, as shown below.



- When this "selection" effect is combined with the available modes in the resonant laser cavity, mode selection is further restricted. The overall result, ideally, is the selection of a single mode of oscillation,

near the high gain region of the laser pulse, as shown below:



Thus, as we can appreciate from Figure 18 and the discussion above, the FP etalon, with its much smaller minor spacing t, passes only those cavity modes which are a distance c/2t apart. Since the gain in the original laser pulse decreases on either side of λ_0, the overall effect is that only one of the more numerous longitudinal cavity modes, spaced a shorter distance c/2L apart, have sufficient gain and also meet the FP resonance condition to survive and oscillate—as a single mode—back and forth in the laser cavity.

Use of Mirrors

(52) This section will describe some uses for mirrors that have not been mentioned previously. (Recall that earlier, in Figures 5 and 6, as parts of a separate discussion, we have already described the use of mirrors in *searchlights* and various *reflecting telescopes*.)

(53) The law of reflection states that the angle of incidence equals the angle of reflection. If the angle of incidence is increased by one degree (as would be caused by a mirror rotation of one degree) the angle of reflection which must be equal also is changed by one degree. So the angular difference in degrees between the incident and reflected ray is twice the mirror rotation in degrees. This principle often is used for angular magnification.

(54) The simple periscope makes use of mirrors to change the direction of line of sight. One obvious use of such an instrument is on submarines. The periscope allows the crew to elevate their line of sight to one above the water. Figure 19 depicts a simple periscope.

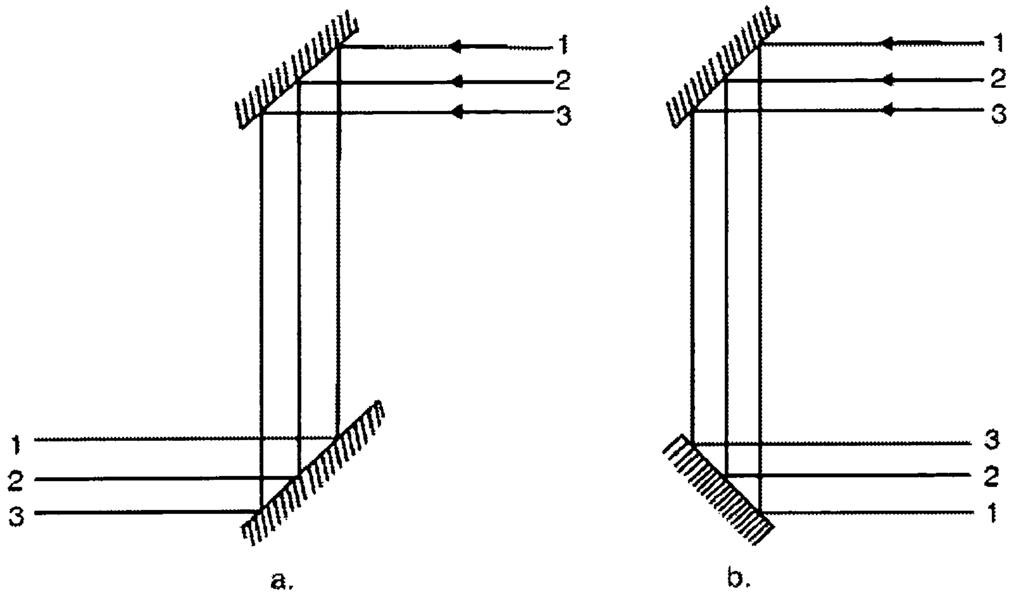


Fig. 19
The simple periscope

(55) This same instrument can be used, for example, to raise or lower a laser beam on an optical table. Note that the three rays on Figure 19a emerge from the second mirror unreversed and that you are looking in the same direction as the periscope. The reversal at each of the two reflections has the effect of canceling the image reversal.

(56) However, in Figure 19b the image is inverted and you're looking in a direction 180° from that of a periscope. Such image reversal is of little importance in most laser applications.

(57) If three mirrors are placed so that they are all at right angles to one another, they form a corner cube. Such an arrangement is shown in Figure 20. A corner cube also is known as a retroreflector because any light striking the device will be reflected back along an exactly parallel path, within the limits of accuracy of the cube's construction. A little geometric study will convince you that three reflections from three orthogonal mirrors will send light back along its original direction.

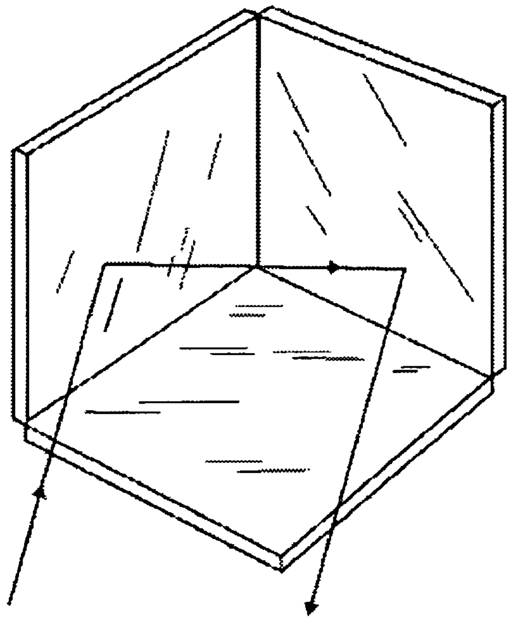


Fig. 20
A corner cube or retroreflector

(58) A device like this was left on the moon by the Apollo astronauts. A laser on the earth was aimed at the retroreflector and, by determining the round-trip travel time of the light pulse, the precise distance to the moon was determined.

(59) Mirrors often are used to scan a beam of light along a surface. Figure 21 is an example of a rotating mirror being used to scan across a collimated beam. One use for such a scan system would put a detector behind an aperture to determine the variation in intensity across a light beam. This device with other optics is used as a flying spot scanner to send pictures for newspapers over telephone lines.

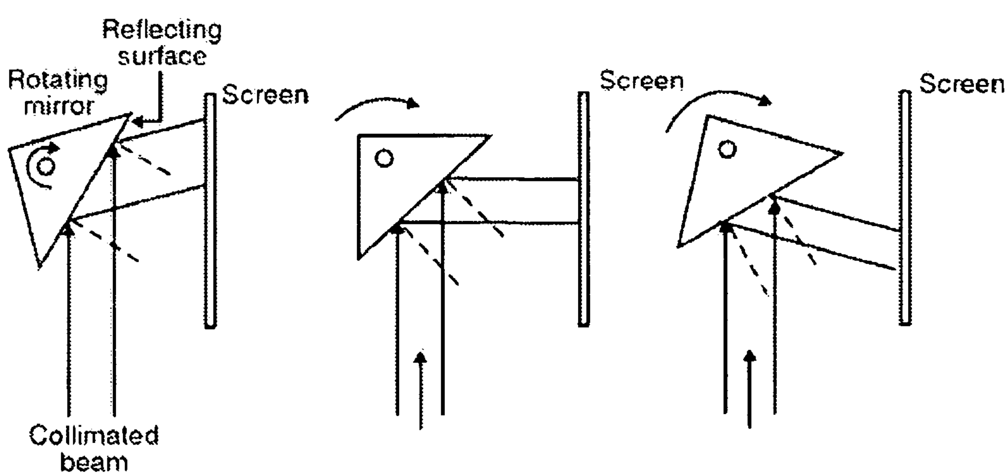


Fig. 21
A rotating mirror used to scan a beam across a surface

(60) The last specific application of a mirror we will mention makes use of the law of reflection to precisely orient a surface in a given direction. For this purpose a mirror target such as shown in Figure 22 can be used. A collimated beam of light is aimed at the mirror target which is attached firmly to the surface being aligned. By rotation of the base surface so that the reflected light exactly returns to the source, the surface normal is caused to point in the direction of the source. Devices of this type are used in survey work.

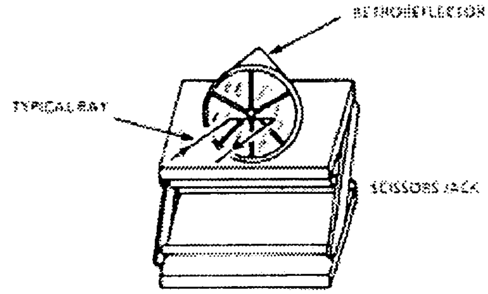


Fig. 22
Magnet-backed mirror for alignment

Specifying a Mirror

(61) The most important question to ask when selecting a mirror to serve a certain purpose is, "Which characteristic of the mirror do you want to use?" When you have decided this, you can write the mirror specifications around this requirement. For example, one of the most important characteristics to specify is the wavelength at which the mirror will be used. If you need a mirror to reflect in the visible but not in the infrared, a mirror described by Figure 23 would be specified.

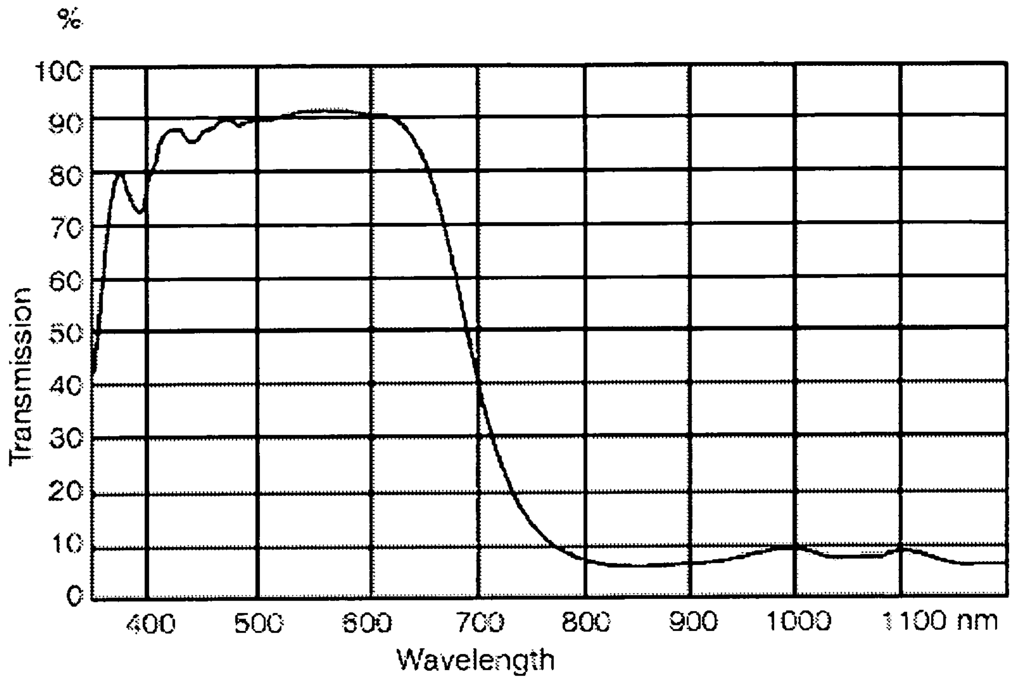


Fig. 23
A cold light mirror

(62) But if the need were the opposite of that stated above, you would use a mirror with properties similar to that described by Figure 24.

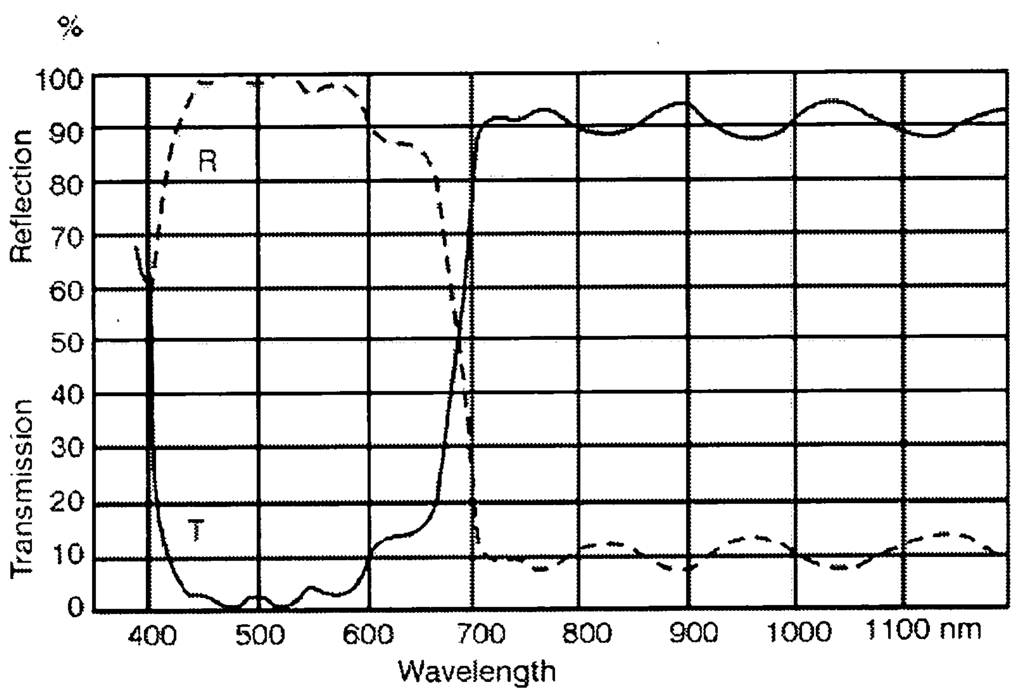


Fig. 24
A heat-reflecting mirror

(63) If the mirror is to be used in an imaging system, you must specify the

focal length and quality of the surface. If the mirror is to be subjected to large temperature variations, you should specify a pyrex or quartz base instead of glass. If the mirror is to be subjected to a lot of handling, specify protective coatings offered by the manufacturer. If the angle of incidence is large for the intended usage, this too should be specified to ensure selection of the right mirror.

(64) In addition to the items mentioned above, any special requirements posed on the mirror by your particular application should be described in the specifications.

EXERCISES

1. Discuss the advantages and disadvantages of front- and rear-surface mirrors.

2. Explain and give one application for each of the following:

   - Dielectric-coated metal mirror
   - Hot mirror
   - Cold mirror
   - Fabry-Perot etalon
   - Autoreflection mirror

3. Outline a comparison of the quality and price of laser end reflectors with the given specifications.

   - Diameter 1/2 inch
   - Thickness 0.375 inch
   - For use with argon and krypton laser
   - High-reflectance mirror must be at least 99.7% reflective.
   - Output coupler must have r_1 flat but must have r, with 3 meters

focal length and 5% transmission.

- The cost must remain under $500 for the pair of reflectors.

Compare at least three manufacturers while assembling your outline.

4. From which manufacturer would you recommend purchasing the end reflectors specified in Exercise 3? Using your outline, give the reasons for your choice.

5. Using outside references if necessary, list and explain at least two applications for retroreflectors other than those stated in the text.

6. From a *single* manufacturer obtain the price of three aluminum-coated mirrors of a standard size, say 2.5-cm diameter. The only difference in the mirrors should be surface flatness. Specify perhaps $1/4\ \lambda$, $1/10\ \lambda$ and $1/20\ \lambda$. Make a plot of cost per mirror versus flatness. Give a typical application of each mirror.

7. Using Figure 7, what would be the best metallic coating to use on a flat mirror intended to reflect N_2 laser light near normal incidence? What would be the approximate reflectance of the surface (without over-coating)?

8. Consider a plane, aluminum-coated pyrex mirror that's to be overcoated with MgF and used to reflect a ruby laser pulse at near-normal incidence. What is the approximate percent reflectance of the mirror?

9. A high-quality corner cube prism (similar to the one shown in Figure 25 under *Procedures*) is illuminated with a HeNe laser from a range of 100 meters. The beam strikes the corner cube in such a way that the exit and entrance spots on the cube's face are 1.00 cm apart. The manufacturer of the corner cube states that the angular deviation of the cube is 2.00 arc seconds. By how many centimeters will the center of the retroreflected spot miss the output aperture of the laser?

MATERIALS

HeNe laser

3 Front-surface aluminum mirrors

Scissors jack

3 Mirror mounts

Adjustable iris

Laser power meter

Second-surface mirror

Flat glass plate (optional)

Partially reflective dielectric mirror

Partially reflective aluminum coated mirror

HeNe laser end reflector.

PROCEDURES

Retroreflector

1. Mount two aluminum plane mirrors in mirror holders.
2. Lay the third aluminum plane mirror on the scissors jack and arrange the three as in Figure 25.

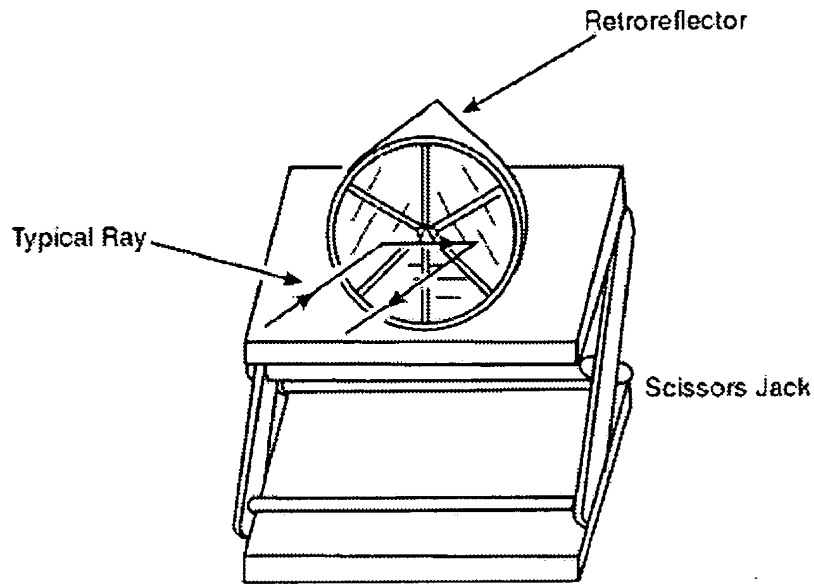


Fig. 25
Mirrors as retroreflectors

3. Adjust the three mirrors to be at right angles to each other. When this is done properly you can see your own eye no matter at which angle you look into the corner reflector.

4. Set the retroreflector arrangement at one end of an optical table and a HeNe laser with an iris in front of it at the other end.

5. Direct the laser beam toward one of the mirror surfaces, observing all standard safety precautions.

6. Close the iris down around the incident beam so that the returning beam can be observed to lie on the iris very close to the incident beam. Mark the location of the reflected beam on the iris.

7. Move the laser and iris to several positions around the table and repeat. The result should be the same, no matter what the entrance angle.

Ghost Images

1. Direct a HeNe laser beam at a second-surface mirror. The incident angle must be large enough so that two or more reflected beams are distinguished. See Figure 26.

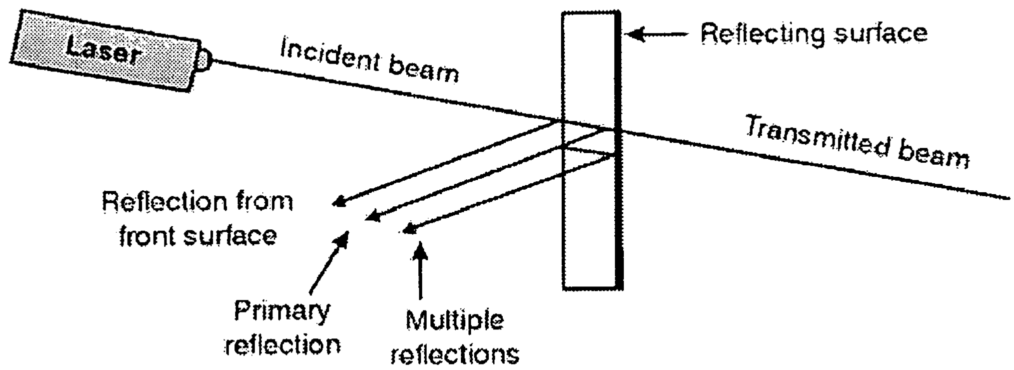


Fig. 26
Reflection from second-surface mirror

2. Measure the intensity of the incident beam with a sensitive power meter. Record your results. For this procedure and those to follow, it will be necessary for you to prepare a data table in which to record your results.

3. Without changing the experimental arrangement, move the power meter detector to a position to measure the intensity of the reflection from the front surface. Record your results.

4. Move the detector to measure the intensity of the reflection from the primary reflecting surface. Then move it to measure the intensity of any multiple reflections and any transmitted beam.

5. Record all intensity measurements in your data table.

6. Calculate the percentage of the incident beam intensity that's reflected from the first surface, the primary reflecting surface and any multiple reflections.

7. (Optional) Perform the same procedure with an uncoated, thick, flat glass plate. In this case, the transmitted beam intensity will be of major concern.

Front-surface Mirrors

1. Replace the second-surface mirror in the above procedure with a partially reflective dielectric mirror. Use a slight angle of incidence (about 10°) and keep it constant throughout the experiment. Again measure the intensity of the incident beam, the transmitted beam and the reflected beam. Calculate the intensity of the beam lost due to absorption and scattering. Assume the difference between the

incident beam intensity and the sum of the reflected beam and transmitted beam intensities is due to absorption and scattering.

2. Calculate the percentage of the incident beam that's transmitted, reflected, absorbed and scattered.

3. Compare your results above with the results you obtain using a partially reflecting aluminum-coated mirror.

4. Use a HeNe laser end reflector, and again compare results.

REFERENCE MATERIALS

Kingslake, Rudolf. "Applied Optics and Optical Engineering." *Optical Components*, Volume 3. New York: Academic Press, 1965.

Smith, W. J. *Modern Optical Engineering*. McGraw-Hill, 1966.

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